Forecasting Research

Forecasting Research Division
Technical Report No. 146

CREATION OF DATA FIELDS REQUIRED FOR EFFECTIVE ROUGHNESS PARAMETRISATION

by

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1. Introduction.

The aerodynamic characteristics of a surface can be described by a surface roughness length, z_o. The roughness lengths of a variety of homogeneous flat surfaces (forest, grass etc) have been evaluated. For heterogenous terrain it is also necessary to account for the influence of orography that is unresolved by the model's resolution, to create an effective roughness length, z_o^{eff}. The effective roughness length can be defined (Mason 1988) as the roughness length value which, in homogeneous terrain, would produce a value of the stress equal to the spatial average of the stress occurring over heterogeneous terrain. Previous to this study the surface roughness values in the LAM were a measure of vegetative roughness only and did not account for orography. The values of vegetation roughness in the LAM were increased as an interim measure until orographic roughness from this work could be included. Hammon and Wilson (1994) showed that the increased roughness produced a clear improvement in the rms wind errors. The U.K. mesoscale model had an effective roughness length ancillary field accounting for both vegetation and orography derived from work by Smith and Carson (1977).

Mason (1985) considered the total drag on the surface to be composed of two parts: a form drag associated with orography and a shear stress associated with surface cover. Mason derived a parametrisation of form drag to account for orography unresolved in models using the parameters h, the peak to trough height and A/S the silhouette area of orography per unit area. He also suggested an algorithm to calculate A/S. Georgelin et al (1994) used Mason's prescription of orographic roughness length in mesoscale model experiments over the Pyrenees and concluded that the scheme may improve the mesoscale simulation of flow over mountainous areas. Mason's method was used by Grant (1991) to calculate orographic roughness length parameters for the U.K. which were then combined with vegetative roughness to form a map of z_o^{eff}. Parameters A/S and h are not new; they were used in a formula devised by Lettau (1969) to calculate a roughness length due to the terrain. Kondo and Yamazawa (1986) defined a parameter similar to A/S called geometrical roughness to account for complex roughness elements such as buildings.

This note records work to create datasets of A/S and h for a new orographic roughness scheme for the mesoscale model which is then extended to all models. Mason's algorithm was used with high resolution orography to calculate the orographic roughness parameters for a limited area of Europe from which ancillary files were created for the U.K. and Bosnia mesoscale models. Section 2 is a description of Mason's parametrisation. Details of the method used to calculate the parameters are in Section 3. As this is a new scheme there is very little information to verify the results against. The new parameters were combined with existing datasets of vegetative roughness length to form a map of effective roughness length for the U.K. mesoscale model. In section 4 the new values of z_o^{eff} are compared with Smith and Carson's values of z_o^{eff}. The area of high resolution orography is limited so the roughness parameters for the rest of the world have to be calculated from lower resolution orography. Section 5 is a study of how sensitive Mason's algorithm for the new parameter A/S is to the resolution of orography. Section 6 is details of attempts to find alternate methods to calculate the parameter followed by the conclusions.

2. The parametrisation of surface drag.

This section is a summary of Mason's parametrisation of surface drag (Mason 1985). To estimate the effective roughness length Mason defines the total surface drag, F_{tot} as

$$F_{tot} = \frac{k^2}{\ln(h/2z_o^{eff})^2}\rho U(h/2)^2 S \qquad (1)$$

where: h is the peak to trough height of the orography;
k is von Karmans constant;
U is the wind speed;
S is horizontal area;
ρ is density.

This total surface drag can be considered to be composed of two parts: a form drag, F_p, that represents the drag due to orography and a shear stress, F_s, representing the type of surface cover.

$$F_{tot} = F_p + F_s \qquad (2)$$

Mason takes the shear stress to be related to the vegetative roughness length, z_0^{veg}, by

$$F_s = \frac{\kappa^2}{\ln(h/2z_o^{veg})^2}\rho U(h/2)^2 S \qquad (3)$$

The form drag can be estimated as

$$F_p = 0.5 C_d A \rho U(h/2)^2 \qquad (4)$$

where A is the silhouette area of the roughness elements in the horizontal area S and C_d is the drag coefficient which Mason takes to be a constant between 0.8 and 0.2.

Using equations 1 to 4

$$\frac{k^2}{\ln(h/2z_o^{eff})^2}U(h/2)^2 = \left[0.5C_d\frac{A}{S} + \frac{k^2}{\ln(h/2z_o^{veg})^2}\right]U(h/2)^2 \qquad (5)$$

which enables z_o^{eff} to be determined as a function of A/S and h.
Equation 6 gives the parametrisation used to calculate effective roughness length. The actual effective roughness lengths used in the models will be calculated during each run and will

include a stability factor, Mason only considered neutral flow.

$$z_o^{eff} = \frac{h}{2}\exp\left[-\frac{k}{\sqrt{0.5C_d\frac{A}{S}+\frac{k^2}{(\ln(\frac{h}{2z_0^{veg}}))^2}}}\right] \quad (6)$$

3. Calculating the parameters A/S and h.

3.1 The orography

The high resolution orography used was terrain elevation data at a resolution of between 3 and 6 seconds, depending on latitude. The data was arranged in degree squares, covering northwest Europe. Figure 1 is a map showing the extent of the data coverage. Small areas of missing data were corrected by searching the surrounding area until real data was found. Large areas of missing data were filled using an existing 5 minute resolution orography map.

3.2 High-pass filtering

The raw orography data was high-pass filtered to form a data set of sub-grid scale orography. The raw orography data was first smoothed by being averaged over a 300"x300" box and then interpolated back to its original resolution. The smoothed version of the orography was subtracted from the original to leave subgrid-scale orography.

3.3 Calculating the parameters

The parameters A/S and h were calculated for each degree square individually at a resolution of 5 minutes. Two sets of maps were created, one from the 3 second resolution data and another using 30 second orography created by averaging the original high resolution data.

3.4 A/S

To obtain a statistical estimate for A/S Mason (1985) suggested using the following formula to determine A/S for a number of 2-D sections with different orientations.

$$A/S = \frac{\sum H(\Delta h)\Delta h}{L} \quad (7)$$

where L is the length of the section, Δh is the change in height between adjacent points on the section and H(x) is the step function defined by

$$H(x) = \begin{cases} 1 & \text{for } x > 0 \\ 0 & \text{for } x \leq 0 \end{cases} \quad (8)$$

The value of A/S assigned to each 5 minute grid square was an average of A/S values calculated for six 2-D sections crossing the grid square in different directions, as used by Grant (1994).

3.4 Peak to trough height, h

Mason (1985) suggested that h, the peak to trough height, be taken as the mean of the main height changes between distinct peaks and valleys. In this study, h was determined from the height variance, σ_h^2, using the equation assumed by Grant (1994):

$$h = 2\sqrt{2}\,\sigma_h \qquad (9)$$

3.5 Results

Figure 2 is a map of A/S calculated from the 3 second data. The values of A/S range from 0 to 0.25 with the largest values over mountainous regions such as the Alps, the Pyrenees and Scandinavia. Figure 3 is a map of h calculated from the 3 second data. The values of h range from 0 to around 2000m with highest values also occurring over mountainous regions. Mason and Grant (1990) calculated A/S and h using Mason's method over the Black Mountains of South Wales using an Ordnance Survey map. They assigned A/S and h values of 0.10 and 270m respectively. These compare well with the new values for the same area: A/S between 0.08 and 0.09 and h between 300m and 400m.

4. Effective roughness length for U.K. mesoscale model

4.1 Existing U.K. mesoscale dataset of z_o^{eff}

The effective roughness length used in the U.K. Mesoscale model prior to this study was derived from a map formed by Smith and Carson (1977) and covers mainland Britain only. Over non mountainous regions the map was formed on a 10km grid by inspecting Ordnance Survey charts. Each 1km square was assigned a value of geostrophic drag coefficient corresponding to its topography and surface cover. These individual values were averaged to produce an effective value of geostrophic drag for each 10x10km square from which a map of effective roughness could be derived. Over hilly regions the effective roughness length was assumed to be proportional to the product of a characteristic slope and the peak to trough height. Smith and Carson describe this formula as "basically unverified." This section describes how the new dataset of z_o^{eff} was formed from A/S and h and compares it with Smith and Carson's dataset.

4.1 Calculating effective roughness length

The datasets of A/S and h were interpolated to the U.K. mesoscale model grid. Equation 6 was used to create a new effective roughness length map using the current mesoscale model dataset of vegetative roughness and C_d equal to 0.3 as used by Grant (1994).

4.2 Man made structures

The orography data does not contain details of building heights so the effect of urban areas is missed. Around London Smith and Carson's mesoscale dataset has values of effective roughness length between 0.6 and 1.0 metres - the new method produces values of only 0.1 metres. It was decided to artificially create values for London in the mesoscale datasets. Fourteen grid points were altered, the values of A/S were set between 0.025 and 0.035 and h in the range 100 to 200 metres. The current value for z_o^{veg} in the London area is 0.014 metres, this together with equation 6 produced new values of effective roughness lengths similar to Smith and Carson's values. Figure 4 is a graph of A/S against roughness length calculated using equation 6 for various values of h.

4.3 Results

Figures 5 and 6 are maps of A/S and h calculated from 3 second orography for the Mesoscale grid. A/S has a maximum value of around 0.14 in Scandinavia, and south west Scotland although most of the area has a value below 0.03. The highest value of h is around 900m and occurs over Scandinavia. The highest value in Britain is 700m over Scotland. Most of the area has a value of h below 100m.

Figure 7 is the effective roughness length for the mesoscale model calculated using equation 6 and the data from figures 5 and 6. The majority of the area has an effective roughness length below 0.5m. The largest values are over mountainous regions, reaching nearly 30 metres over Scandinavia and around 22m in the Highlands of Scotland. This can be compared with the current Mesoscale dataset of roughness length, which covers the U.K. only (Figure 8). Again z_o^{eff} over most of the region is below 0.5m with a maximum value of around 20m in Scotland. The two maps of z_o^{eff} have broadly the same shape although Smith and Carson's has generally higher values.

Figure 9 is a difference map of the new effective roughness length minus the current one. Most disagreement between the two datasets occurs over mountainous regions. The new dataset is between 1 and 4 metres smaller than Smith and Carson's in Wales, the Peak District and parts of the Lake District and Scottish Highlands. There are also areas where the new dataset is larger: the Southern Uplands of Scotland and central Lake District. The largest disagreement is in the Highlands where the new dataset varies from being 14 metres smaller to 8 metres larger than Smith and Carson's. Part of the Scottish Highlands were looked at in more detail:

4.4 Study of the Grampian Highlands

Figure 10 shows an enlarged section of the difference map in a region of the Grampian Highlands, (56-57 N and 3-6 W). In the centre of the area the new dataset is up to 16 metres smaller than the current one while at the northernmost edge of the region the new dataset is approximately 8 metres larger.

Figure 11 is the new dataset of effective roughness length for the same region, figure 12 is Smith and Carson's values. A comparison of the two shows that in this region of Scotland the 2 datasets of z_o^{eff} have very different shapes. Figure 11, the new dataset, has an area of low z_o^{eff} (2-8 m) in the centre and to the east of the region with two peaks in the northwest where z_o^{eff} is as high as 22 metres. Smith and Carson's dataset for this area, figure 12, has

much less detail and is a very different pattern with one ridge of high z_o^{eff} (16-18 m) running east-west through the centre of the area. Figure 13 is the 3 second orography for this region it matches maps of the area well. The large differences between the two z_o^{eff} datasets can be explained by the greater accuracy of the new dataset. The region of relatively low values in the east of the new dataset corresponds to a flat valley with a number of lochs that is completely missed by Smith and Carson's coarser resolution. The two peaks of z_o^{eff} to the west of the region in the new dataset are Ben Nevis and the mountains to its west with Glen More running between them. Again this detail is not represented in Smith and Carson's datasets of z_0^{eff}.

5. A comparison of A/S calculated from different resolution orography.

At present the coverage of the high resolution data is limited to Europe so the values of A/S and h for the rest of the globe have to be calculated from lower resolution orography. Mason's algorithm for calculating A/S is very sensitive to the resolution of orography, Mason (1985) noted that the value of A/S will be greater the finer the resolution of the orography. The peak to trough height, h, is calculated from standard deviation of orography and is not very sensitive to the resolution of orography used.
A global 5 minute orography dataset was used with Mason's algorithm, equations 7 and 8, to calculate A/S on a one degree resolution, the results were compared with those from high resolution data to see if this extension is viable. First there is a comparison of the parameter, A/S, calculated on 5 minute resolution over the extent of the high resolution data using 3 and 30 second orography.

5.1 A comparison of A/S calculated on 5 min resolution over the extent of the high resolution data area using 3 and 30 second orography.

Figure 14 is a difference map of A/S from 3 second orography minus that from 30 second resolution. As expected the values of A/S from 3 second resolution orography are generally larger than those from 30 seconds. The discrepancies increase with A/S so the largest differences occur over mountainous areas, over the Alps the values of A/S from 30 second are up to 30% smaller then those from 3 second orography. Figure 15 is a plot of the data. There are 42000 points but only 5 have values of A/S from 30 second orography greater than 0.20
In order to find a relationship between the data from the two different resolution orographies several different linear multivariate, nonlinear and spline curves were fitted to the data. Simple quadratic and cubic polynomials produce close fits in the range of data but are useless for extrapolation. For example,

$$Y = aX_1 + bX_1^2 + cX_1^3 \qquad \textbf{(10)}$$

where: X_1 is A/S from 30 second orography;
Y is an approximation to A/S from 3 second orography;
a=1.94; b=-6.97; c=18.99.

Figure 16 is a graph of this curve that can be compared with figure 15, the plot of A/S from 3 second orography versus that 30 second, to assess its fit. It is a good fit to the data but is not valid for extrapolation since beyond the range of the data as it increases with X_1^3 .

A safe guess of behaviour beyond the data range might be to have the equation tend to X=Y beyond the range of the real data e.g.

$$Y=aX_1e^{-bX_1^2}+X_1 \qquad (11)$$

where: X_1 is A/S from 30 second orography;
Y is an approximation to A/S from 3 second orography;
a=0.76; b=37.0.

Figure 17 is a graph of this equation. It fits the data of figure 15 as well as the cubic polynomial. Beyond X_1=0.24 the curve tends to X_1=Y.

Alternatively it may be desirable to have the equation reach a limit e.g.

$$Y=a(1-e^{bX_1}) \qquad (12)$$

where: X_1 is A/S from 30 second orography;
Y is an approximation to A/S from 3 second orography;
a=0.34; b=5.5.

Figure 18 is a graph of this curve. Again it fits as well as the cubic polynomial. As X_1 increases beyond 0.24, Y tends to a limit of 0.34.

5.2 Comparison of A/S from 5 minute orography with A/S from 3 second orography

The global 5 minute orography was used to calculate A/S at one degree resolution using Mason's algorithm. (The orography data was not filtered). This data was interpolated to form datasets of A/S on model grids. Parameters with resolution of one degree are not a measure of sub-grid scale features so the values of A/S calculated from 5 minute orography will be much lower than those calculated from high resolution orography. The values of A/S from low resolution orography were compared with values of A/S calculated using 3 second orography over the extent of the high resolution data for different models. It was hoped that a relationship could be found between the values of A/S calculated from the different resolution orographies so that valid global datasets of A/S could be formed using the 5 minute orography. The value of A/S depends on the resolution it is calculated on, A/S will be lower on coarser resolution grids than on fine ones, so different models will need different equations. The climate, global and limited area and mesoscale models were tested.

The 2 sets of A/S from high and low resolution orography were compared for the U.K. and Bosnia mesoscale models. Figure 19 is a plot of A/S from 5 minute resolution orography versus A/S from 3 second orography for the U.K. and Bosnia mesoscale grids. The maximum value of A/S from 5 minute orography is 0.024 compared with 0.24 from high resolution data. On average the values of A/S from low resolution data are around a factor

of 7 smaller than those from high resolution but the points are very scattered.
A number of linear; non linear and spline curves were fitted to the data but none were convincing within the data range or for extrapolation beyond it. For example

$$Y = aX_1 + bX_2 \quad (13)$$

where: X_1 is A/S from 5 minute data;
X_2 is h from 5 minute data;
Y is an approximation to A/S from high resolution data;
$a = 5.14$; $b = 5.36 * 10^{-5}$.

Figure 20 is a plot of this equation. It can be compared with figure 19, the plot of A/S from high resolution against that from low resolution orography, to assess the fit.

Figures 21, 22 and 23 are plots of A/S from high resolution orography against A/S from 5 minute orography for the limited area, global and climate model resolution respectively. For the LAM the values from the low resolution data are around 6.6 times lower than those from the high resolution. For the global model the scaling factor is around 6.2 and for the climate it is 5.5. These scaling factors can be applied to the data and will produce values of A/S around the correct magnitude but because of the data is very scattered they will miss out a lot of details.

6. Deriving A/S from standard deviation

A/S is a measure of the density of roughness elements which is related to the variance of the orography. Work was done to redefine A/S from σ, the standard deviation of 10 minute orography already included in the models orography fields files. The values of A/S calculated from Mason's algorithm using 3 second orography were compared with the values of σ from 10 minute orography over the extent of the high resolution data. For each model I attempted to find a relationship between the two, that is find an equation that could be applied to σ from 10 minute orography to obtain values of A/S similar to those that would have been obtained using Mason's algorithm and high resolution orography.

6.1 LAM

Figure 24 is a plot of A/S calculated using 3 second orography against σ from 10 minute orography for the extent of the high resolution data for the LAM grid. The data is very scattered but a straight line was fitted with a gradient of 0.00030. A new dataset of A/S for the LAM was created using the standard deviation of 10 minute orography and the simple linear equation;

$$Y = aX \quad (14)$$

where Y is the calculated value of A/S, X is σ of 10 minute orography and $a = 0.00030$.

Figure 27 is a difference map of A/S calculated using Mason's algorithm and high resolution minus that calculated from σ. The values of A/S calculated from σ are up to 0.06 too low over the Alps, Scotland and Wales. The dataset of A/S calculated from σ of 10 minute orography does not include details such as the region of high A/S over Norway and the area of low A/S in Northern Italy.

6.2 Global model

Figure 25 is a plot of A/S from 3 second orography against σ from 10 minute orography for the extent of the high resolution data for the global model grid. A straight line was fitted with a gradient of 0.00016. A new dataset of A/S for the global model was created using the standard deviation of 10 minute orography and equation 14 with a=0.00016. Figure 28 is a difference map of A/S from high resolution minus that calculated from σ of 10 minute orography for the Global model. As with the LAM the values of A/S calculated from σ are up to 0.06 lower than the values from Mason's algorithm and high resolution orography over the Alps, Scotland and Wales. The values calculated from σ do not include the area of high A/S over Norway or the region of low A/S around Northern Italy.

6.3 Climate model

Figure 25 is a plot of A/S from 3 second orography against σ from 10 minute orography for the extent of the high resolution data for the climate model, the points are not very scattered but there are only 100 points compared with 5000 for the LAM. A straight line was fitted with a gradient of 0.00008. A new dataset of A/S was created using equation 14 with a=0.00008. Figure 29 is a difference map of A/S from high resolution minus that calculated from σ. The values of A/S calculated from σ are up to 0.02 too low over the Alps, Scotland and Wales and completely miss out the area of high A/S over Norway.

The results of using simple linear equations to calculate A/S from σ of 10 minute orography are not very accurate. The values of A/S are too low over mountainous regions and miss some detail out completely. (The difference maps figures 27,28 and 29 are available in colour on Mosaic under my home page). But until higher resolution data becomes available for the rest of the globe or a new method to calculate A/S is derived these rough approximations will be used in the model.

7. Conclusion

Mason's algorithm can be used with high resolution orography to calculate accurate maps of the roughness length parameters A/S, the silhouette area of orography per unit area. The values of A/S calculated using this method are very dependant on the resolution of the orography used. Using coarser orography loses detail and the values of A/S are smaller. 5 minute orography produces values of A/S around 6 times smaller than those calculated from 3 second orography. Until high resolution orography can be obtained for the rest of the globe the values of A/S for the global, climate and limited area models must be obtained from low

resolution orography using the best and most scientifically defensible formula. The values of A/S calculated using Mason's algorithm and from 5 minute orography are not a measure of subgrid-scale orography; they can be scaled up to create values of A/S of approximately the correct order of magnitude but there is no justification for doing so. The values of A/S calculated from the standard deviation of orography produce values in the correct range but without detail, as A/S is a measure of σ_h it was decided to use these values in the model. The formula for calculating peak to trough height from standard deviation of orography is not very sensitive to the resolution of orography used so for the climate, global and limited area models the values of h were calculated using the 10 minute orography data.
The impact of the orographic roughness in the unified model is described in three reports. Milton et al (1994a) contains a description of the new scheme, Wilson and Hammon (1994) reviews parallel trials of the scheme and Milton et al (1994b) describes the revised scheme using A/S calculated from σ and results from the parallel trial.
The long term aim is to calculate fields of A/S for the whole globe from high resolution orography using Mason's algorithm. We already have a high resolution orography dataset for the U.S. and work to calculate A/S will start in the spring. The search continues for other high resolution datasets. For version 3.5 the orography will be updated to 5 minute resolution and the values of A/S could be redefined from the standard deviation of 5 minute orography.

References

Georgelin et al, 1994 Impact of subgrid-scale orography parametrization on the simulation of Orographic flows. Monthly Weather Review, 7, 1509-1522

Grant, A. L. M. and Mason P. J., 1990: Observations of boundary layer structure over complex terrain. Quarterly Journal of the Royal Meteorological Society, 116, 159-186

Grant, A. L. M., 1994 A roughness Length Map of the UK. unpublished APR document

Hammon, O and Wilson, C 1994 Forecasting Research Division Technical report No.95

Kondo J. and Yamazawa,H., 1986: Aerodynamic roughness over an inhomogeneous ground surface. Boundary Layer Meteorology, 35, 331-348

Lettau H., 1969: Note on aerodynamic roughness-parameter estimation on the basis of roughness-element description. Journal of applied meteorology, 8, 828-832

Mason P. J., 1985, On the parametrization of orographic drag. ECMWF seminar 1985, Physical parametrization for numerical models of the atmosphere, 139-166

Mason P. J., 1988: The formation of areally-averaged roughness lengths. Quarterly Journal of the Royal Meteorological Society, 114, 399-420

Milton S.F., Wilson C., Stratton R.A., Hammon O. and Rawlins F., 1994a Global model

tests. Unpublished F.R. technical note no.127

Milton S.F. Wilson C.A., Hammon O. and Rawlins F., 1994b Revised scheme and second parallel trial. Unpublished F.R. technical note no.139

Smith F. B. and Carson D. J., 1977 Some thoughts on the specification of the Boundary-Layer relevant to numerical modelling. Boundary Layer Meteorology, 12, 307-330

Wilson C.A. and Hammon O., 1994 Parallel suite trial for the global model and limited area models . Unpublished F.R. technical note no.128

Figure 1. Extent of high resolution data

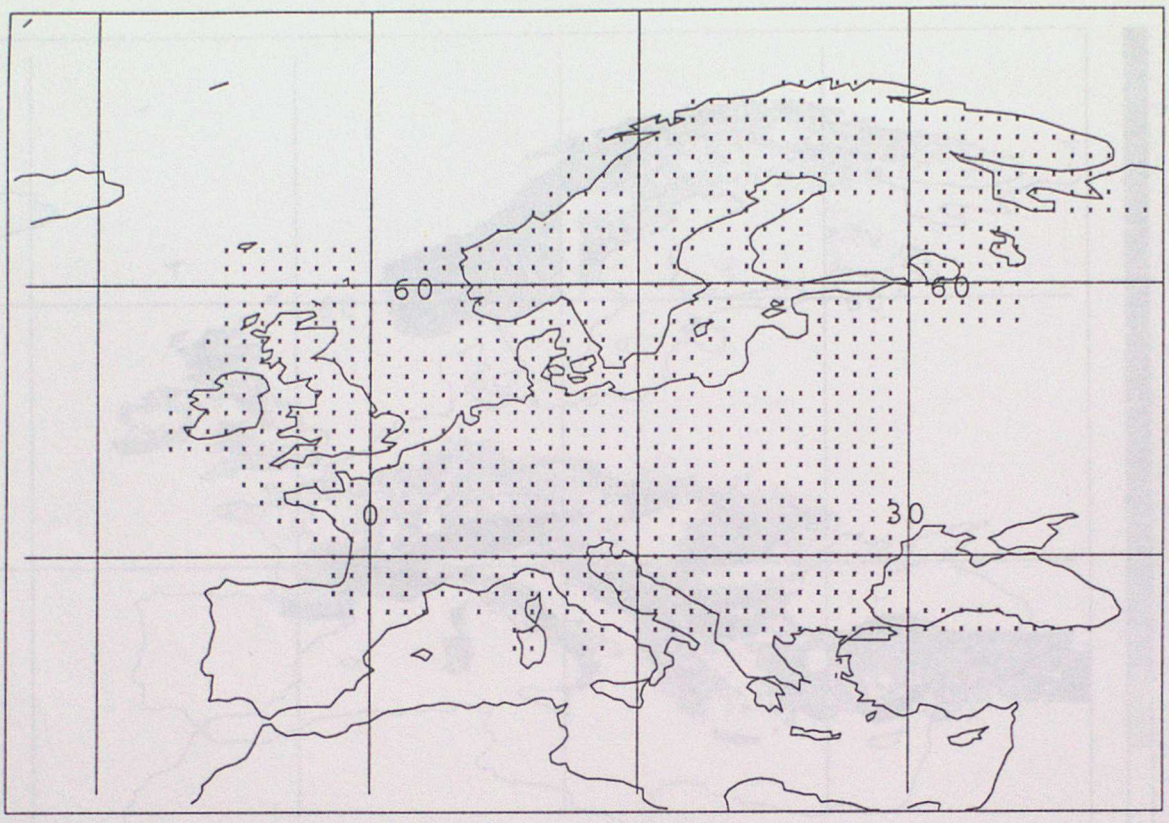


Figure 2. A/S on 5 minute resolution calculated using Mason's algorithm and high resolution orography.

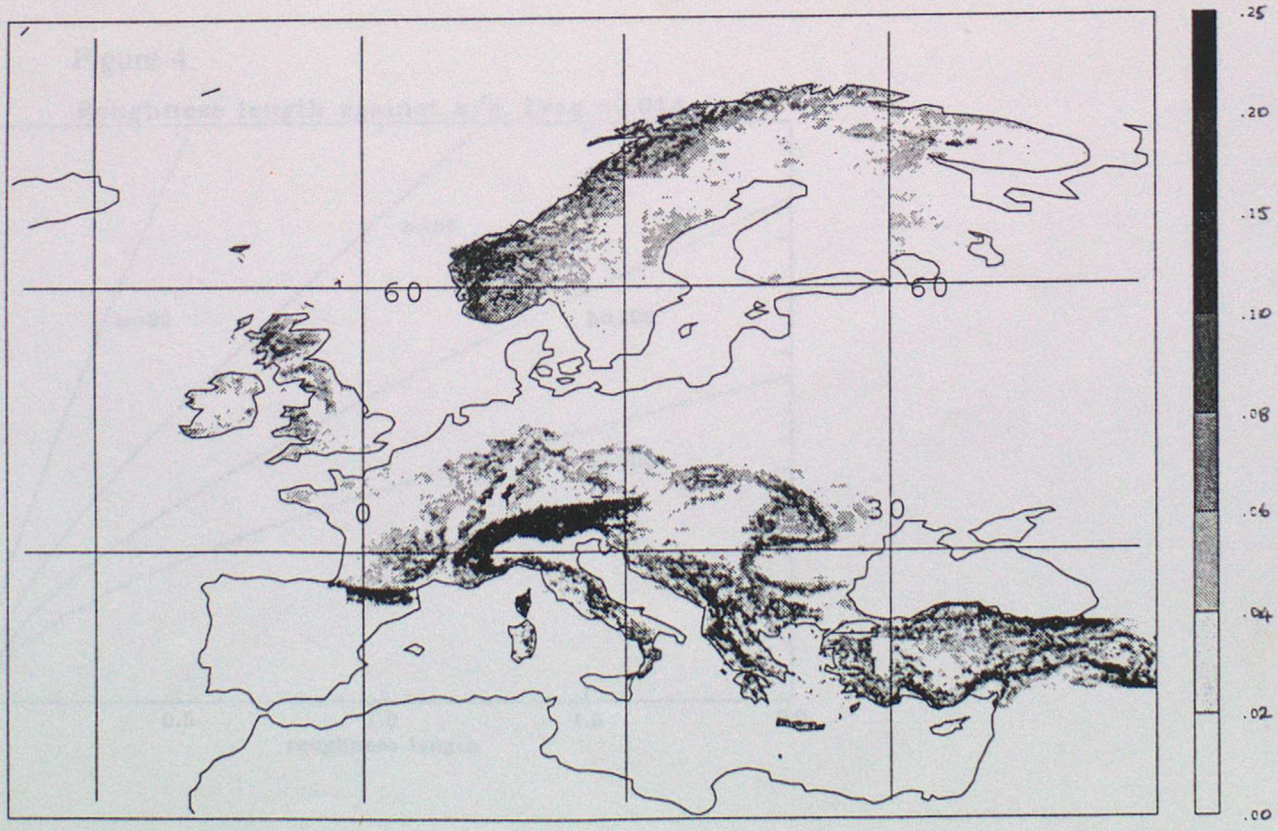


Figure 3. h, peak to trough height, on 5 minute resolution calculated using high resolution orography.

Figure 4.

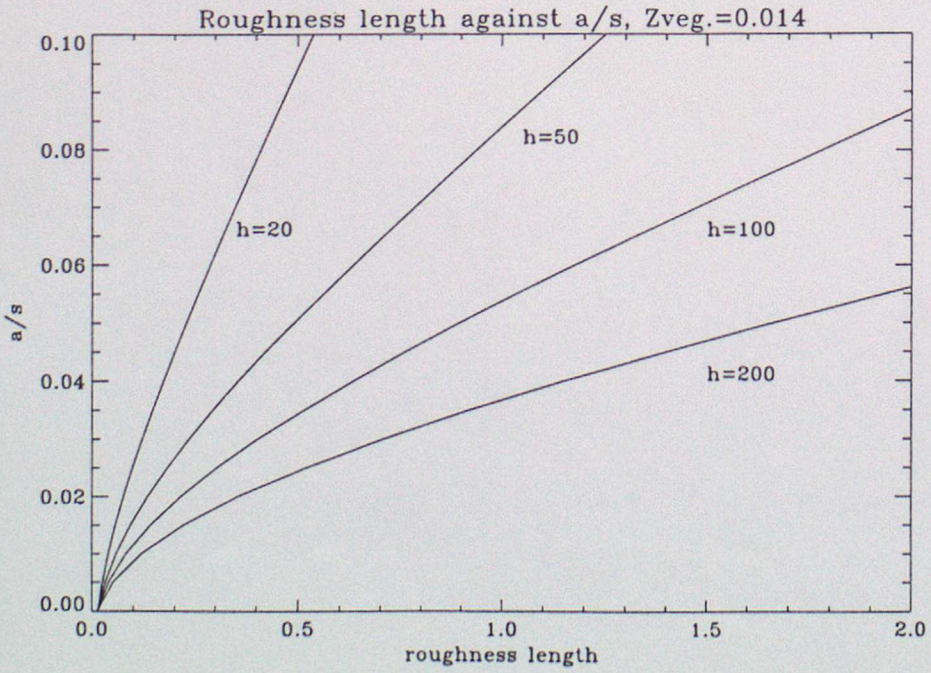


Figure 5. A/S for U.K. mesoscale model. Parameter initially calculated on 5 minute resolution using Mason's algorithm and high resolution orography.

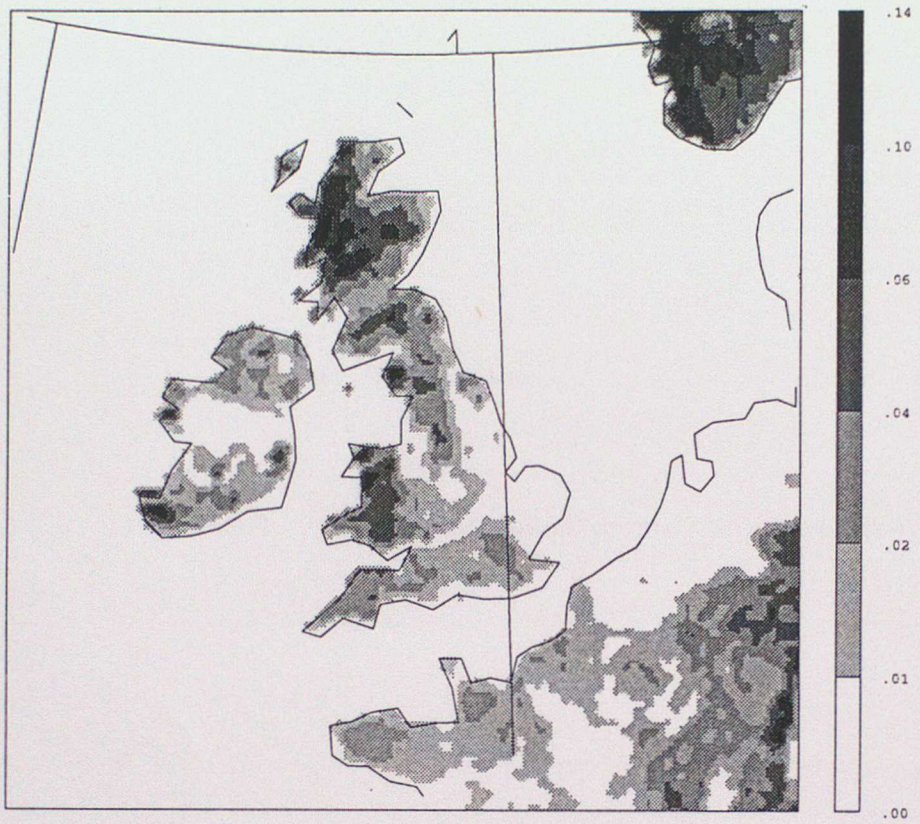


Figure 6. h for U.K. mesoscale model. Parameter initially calculated on 5 minute resolution using Mason's algorithm and high resolution orography.

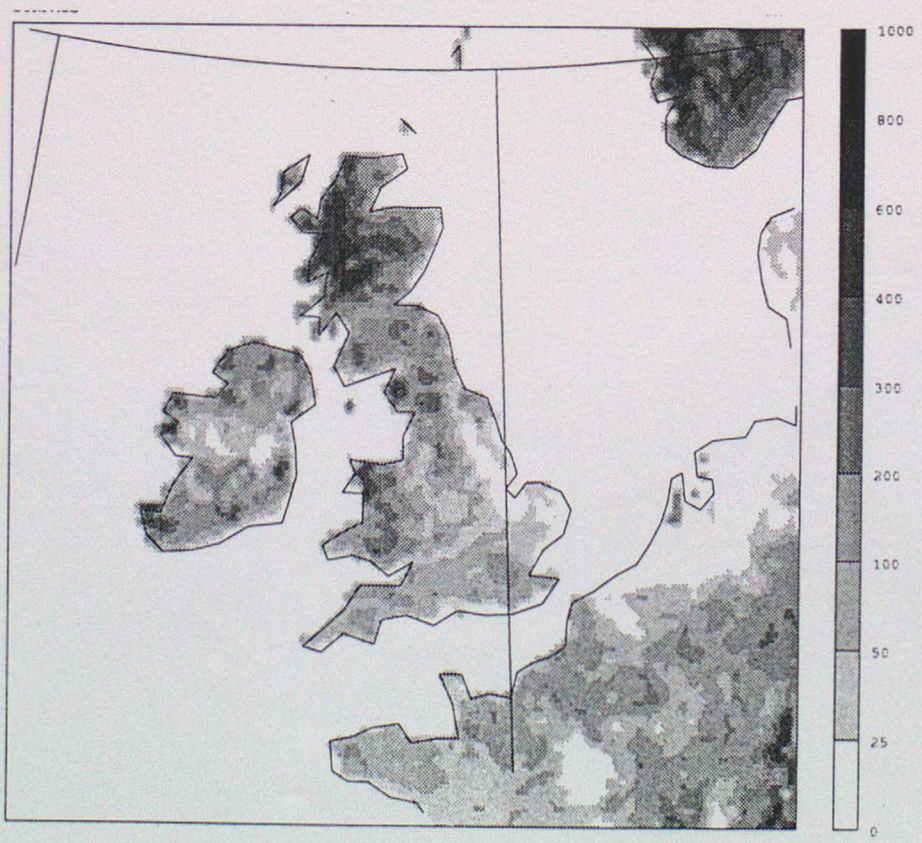


Figure 7. Effective roughness length for U.K. mesoscale model calculated using A/S and h.

Figure 8. Smith and Carson's effective roughness lengths for U.K. mesoscale model.

Figure 9. Difference of 2 effective roughness maps for the U.K mesoscale model. The new values minus Smith and Carson's

Figure 10. New values of effective roughness for the U.K. mesoscale model minus Smith and Carson's (56N–57N,6W–3W)

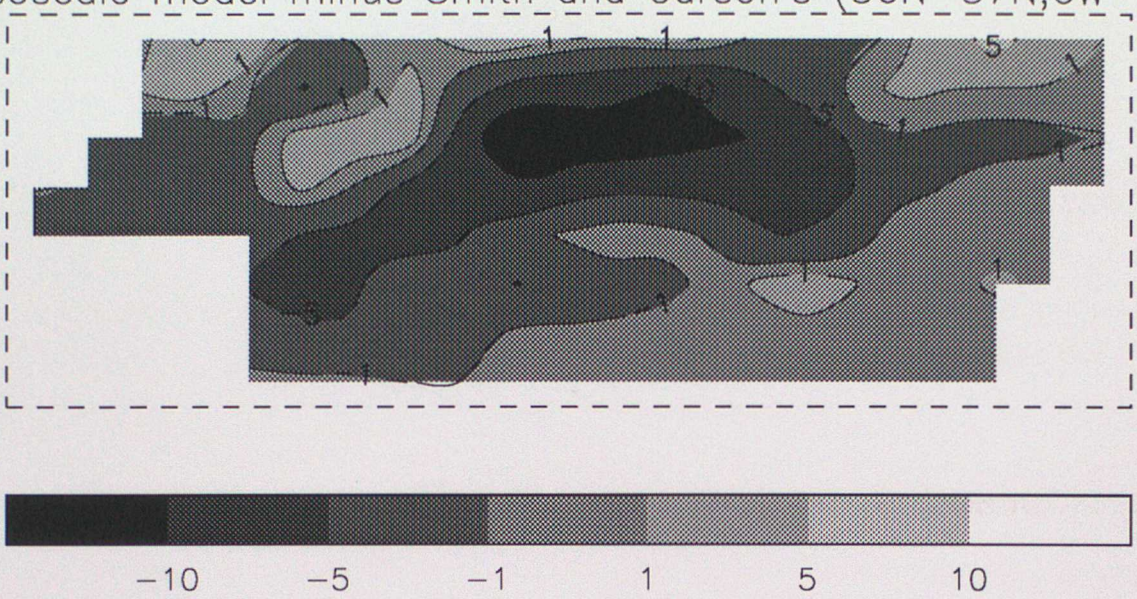


Figure 11. Effective roughness length of U.K. mesoscale model calculated using Mason's method, area 56N–57N, 6W–3W

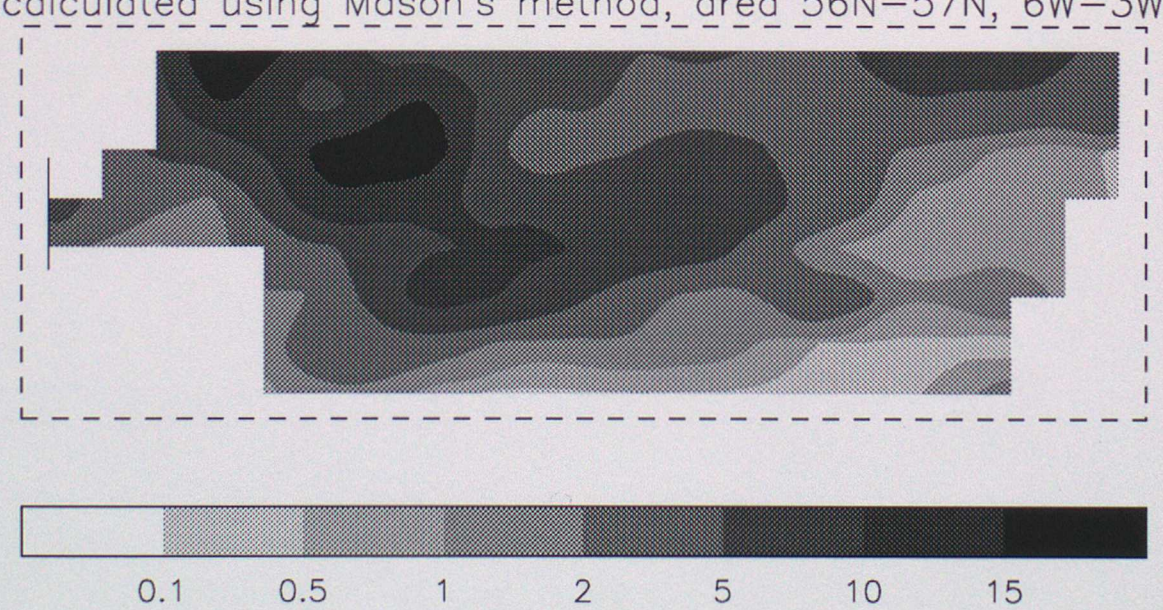


Figure 12. Smith and Carson's values of effective roughness length area 56N–57N, 6W–3W

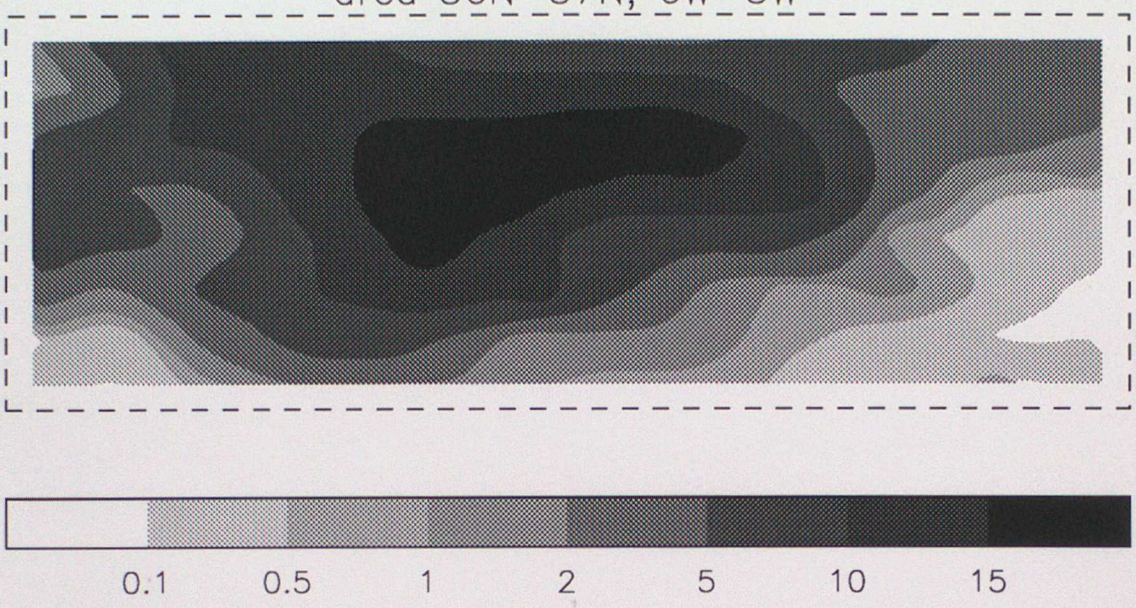


Figure 13. High resolution orography of area 56N–57N, 6W–3W

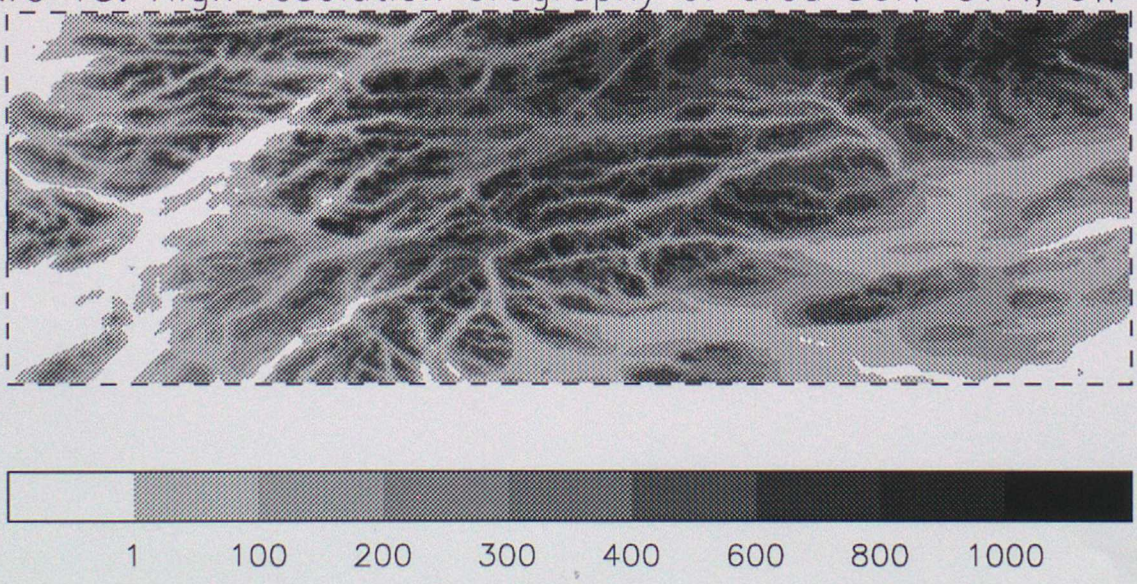
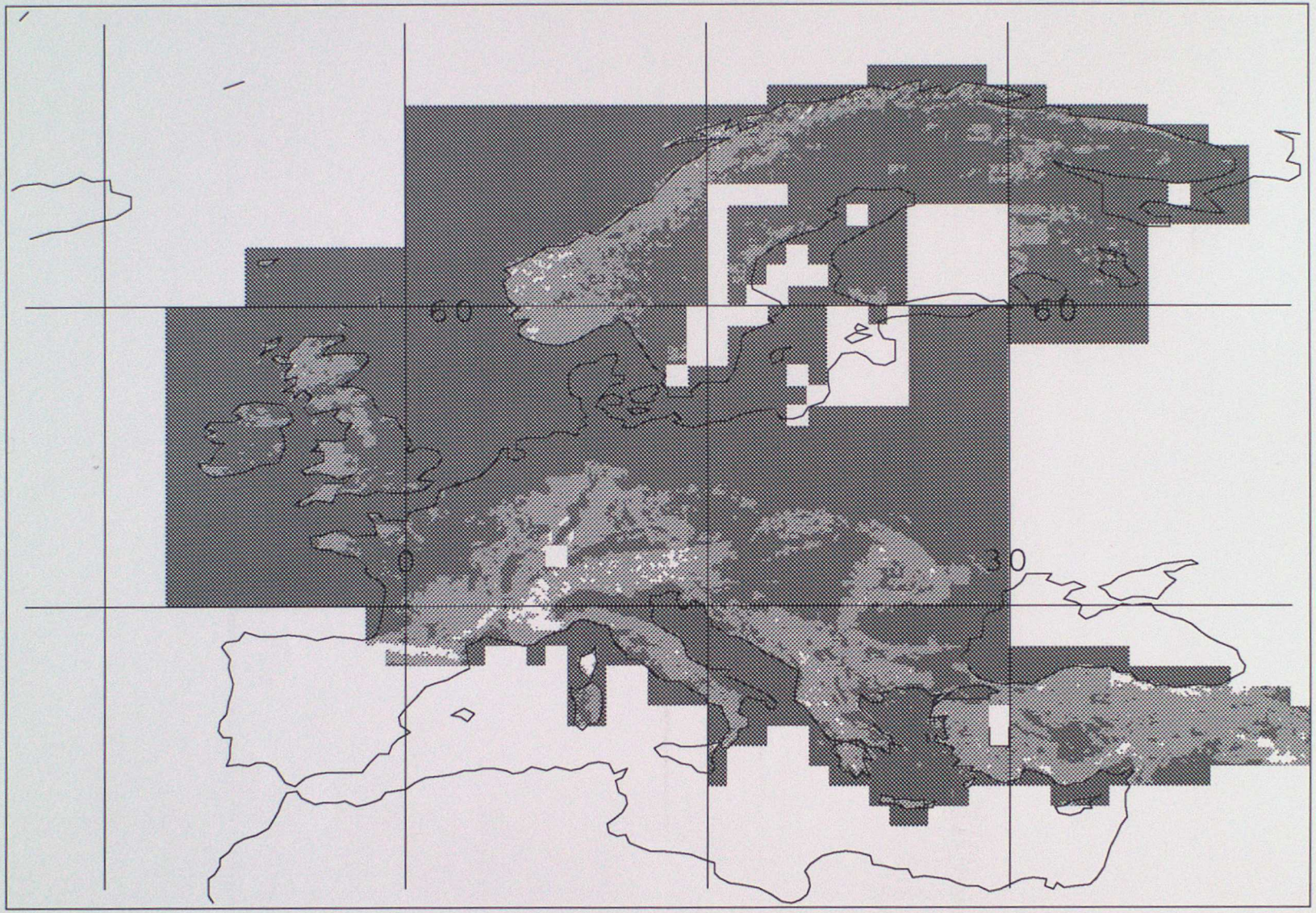


Figure 14. Difference of 2 A/S maps on 5 minute resolution.
A/S calculated using Masons algorithm with 3 second orography
minus A/S calculated using Masons algorithm and 30 second orography.



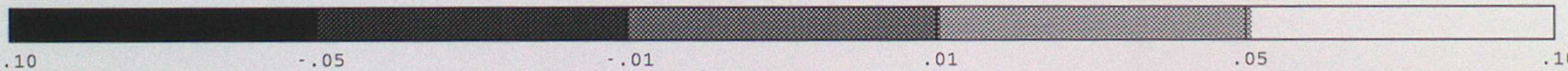


Figure 15. A/S from 3 sec. orog. against A/S from 30 sec. on 5 minute grid.

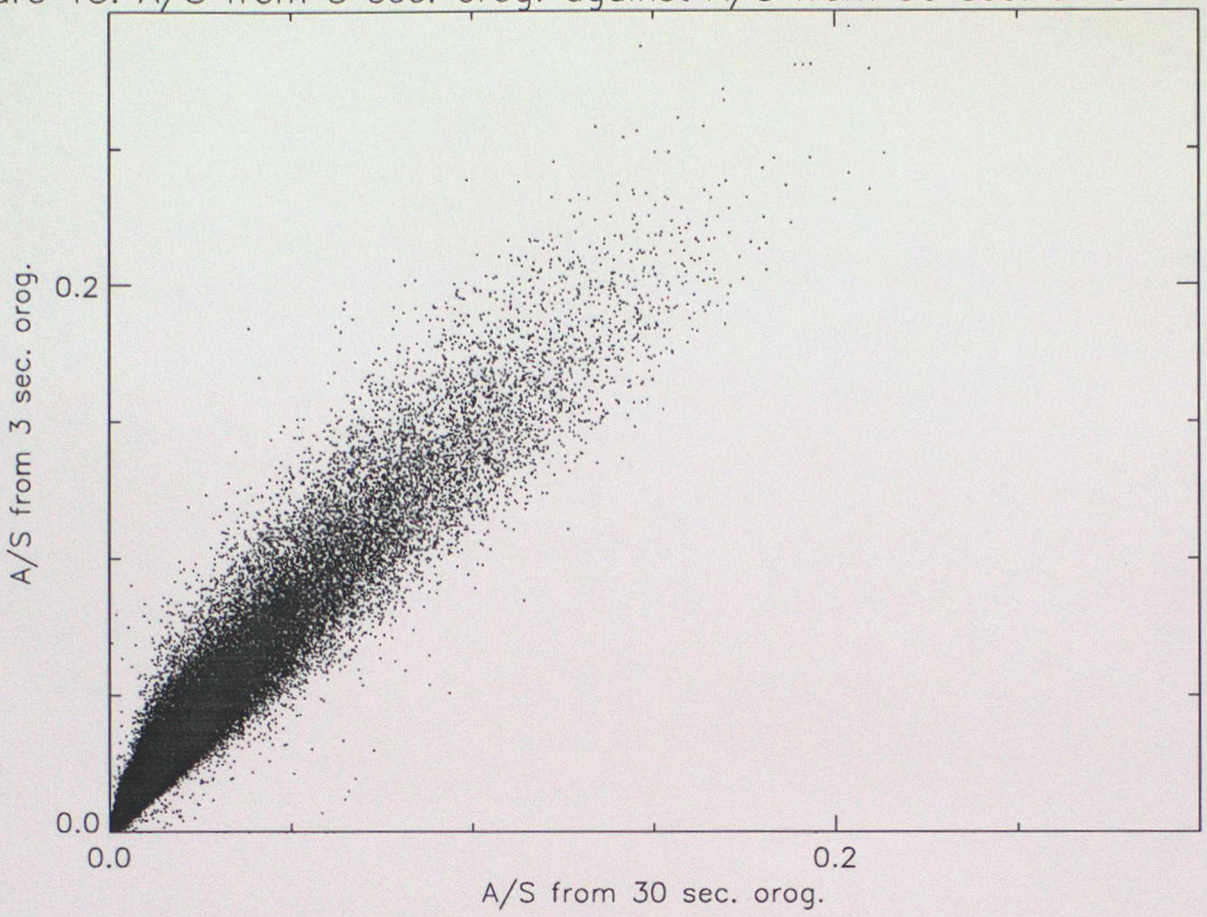


Figure 16. Graph of equation y=ax+bx^2+cx^3

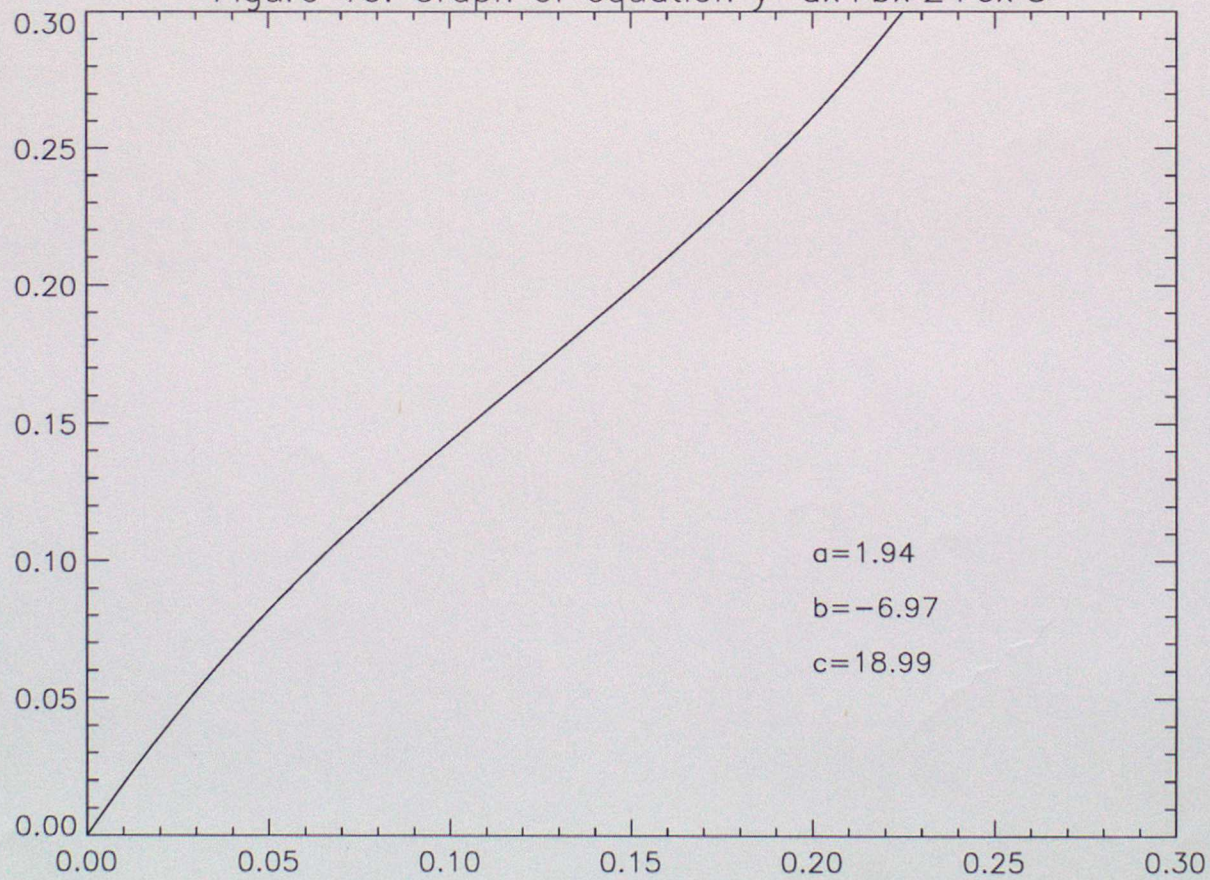


Figure 17. Graph of equation y=ax(exp(−bx^2)+x

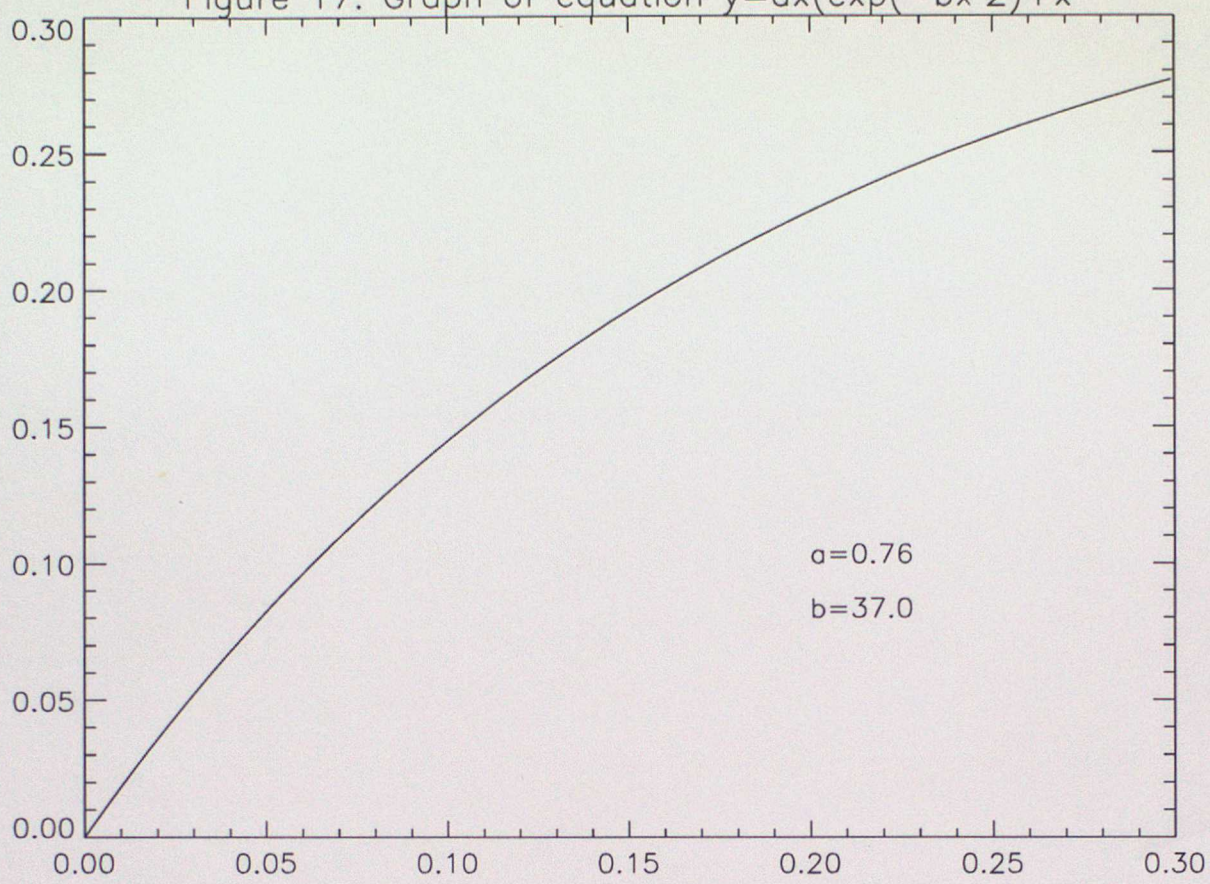


Figure 18. Graph of equation y=a(1−exp(−bx))

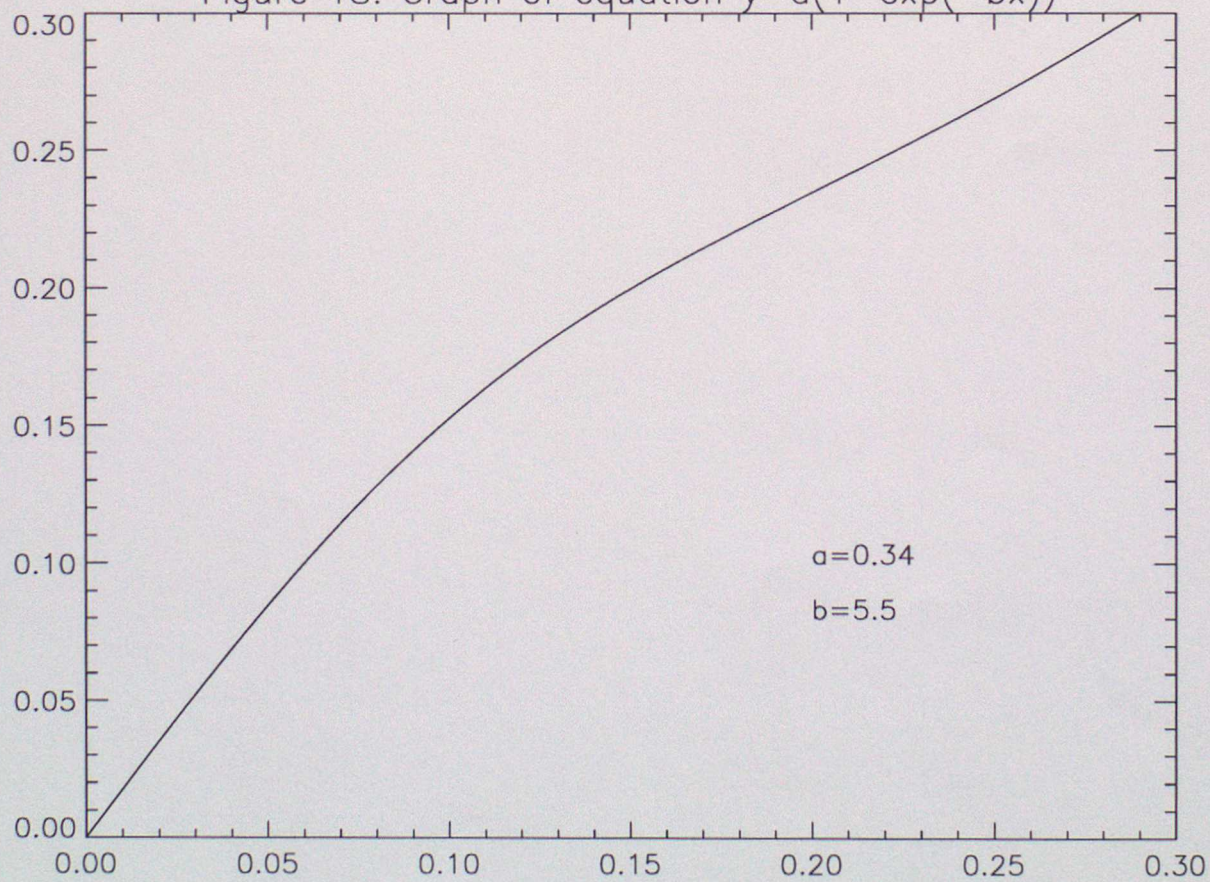


Fig 19. A/S from 3 sec. orog. against A/S from 5 min. for U.K. and Bos mes.

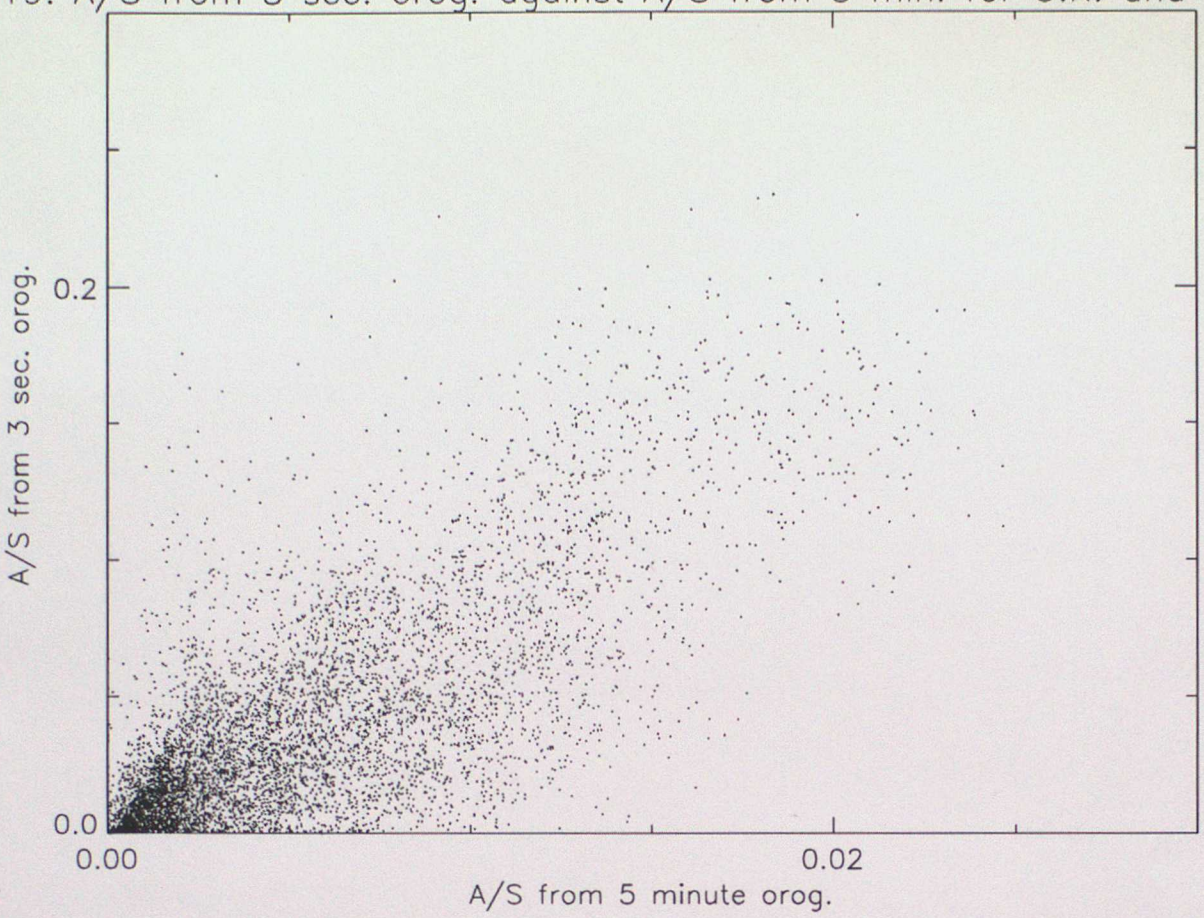


Figure 20. Graph of equation y=ax_1+bx_2

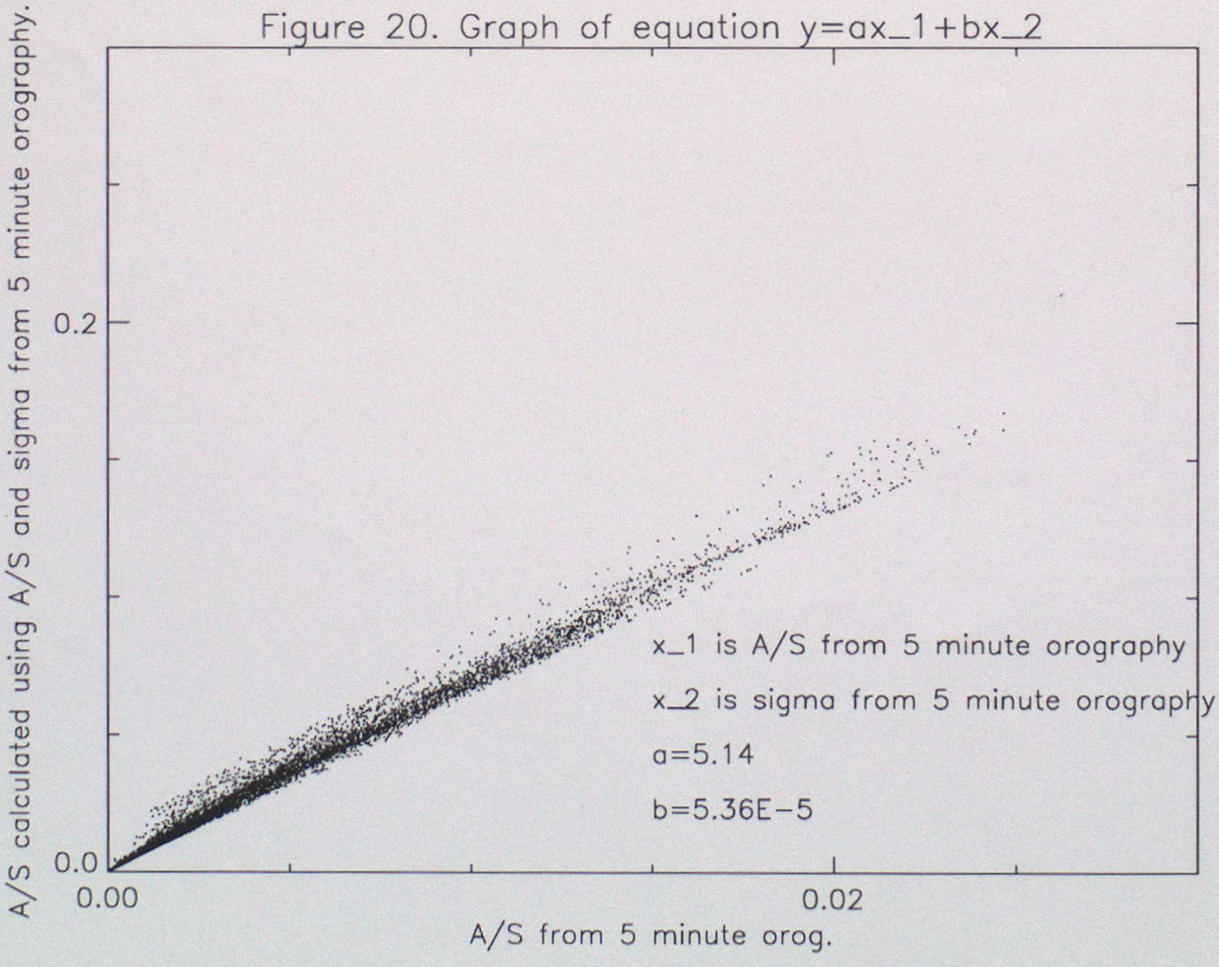


Figure 21. A/S from 3 second orography against A/S from 5 minute orography for LAM

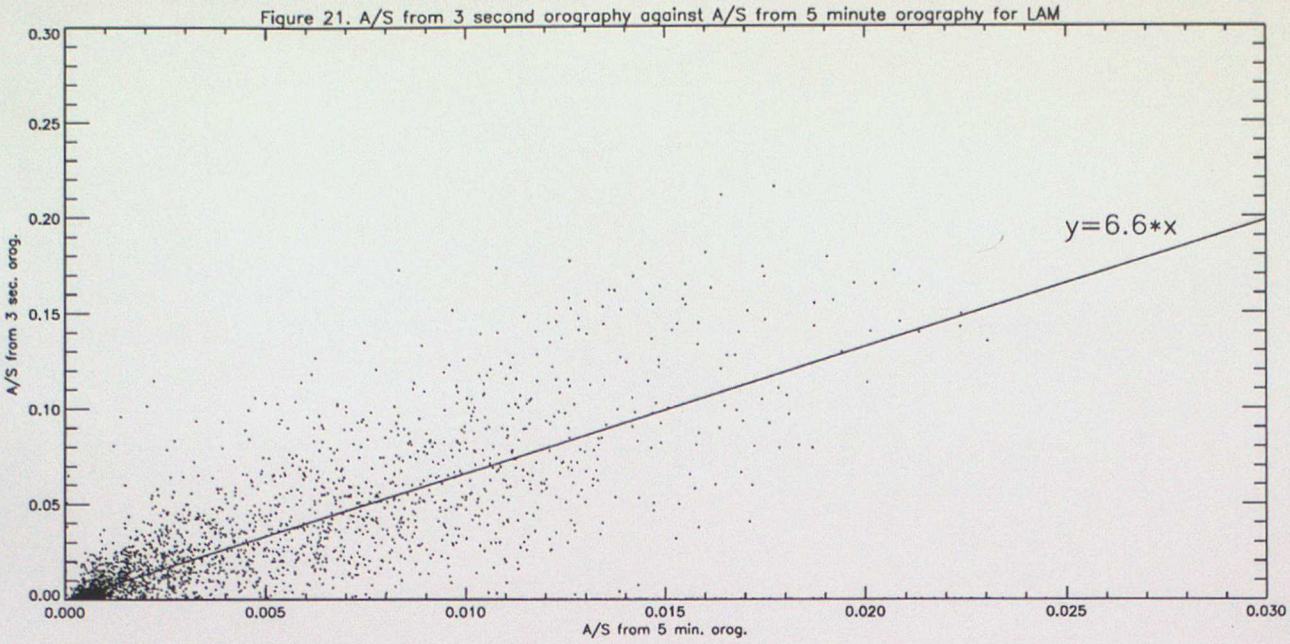


Figure 22. A/S from 3 second orography against A/S from 5 minute orography for global model

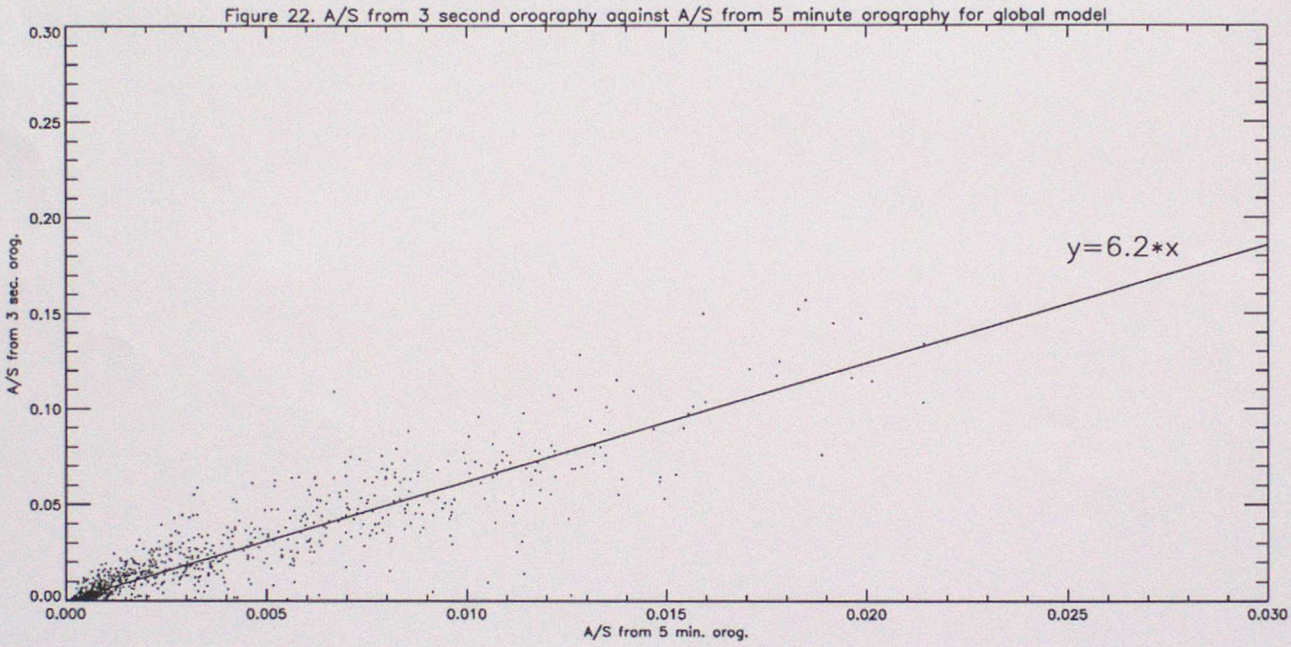


Figure 23. A/S from 3 second orography against A/S from 5 minute orography for climate model

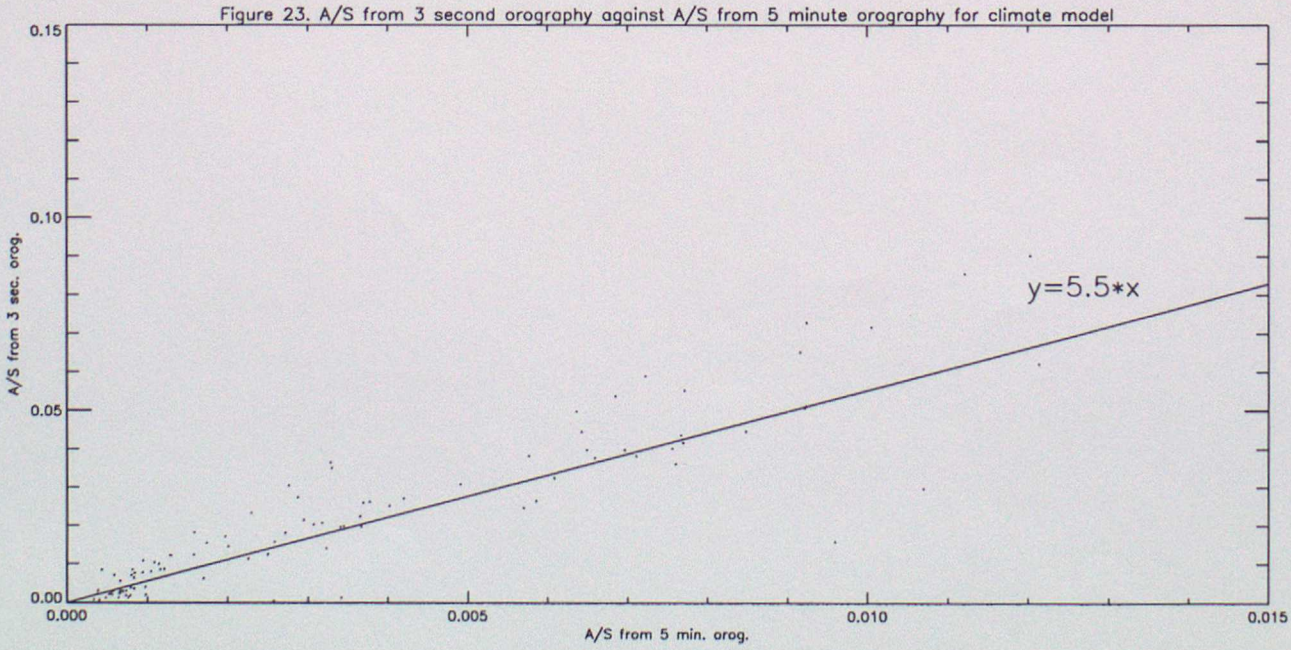


Figure 24. A/S from 3 sec. orog. against sigma of 10 min. orog for LAM

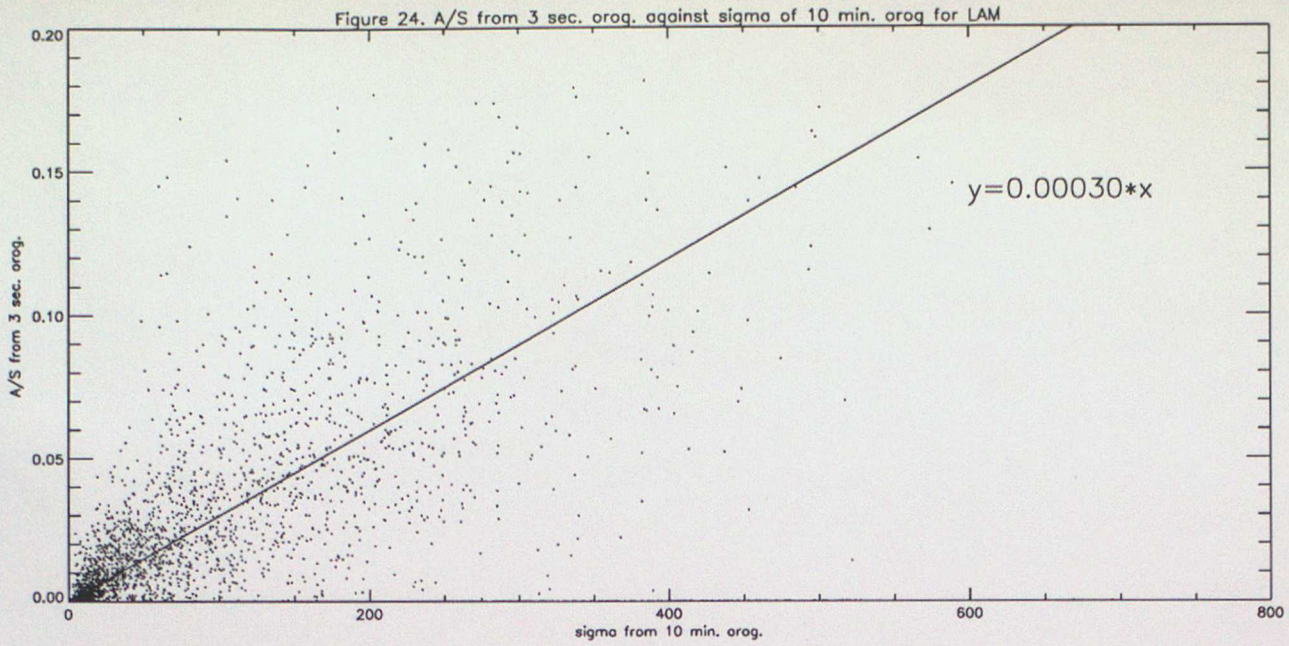


Figure 25. A/S from 3 sec. orog. against sigma of 10 min. orog for global model

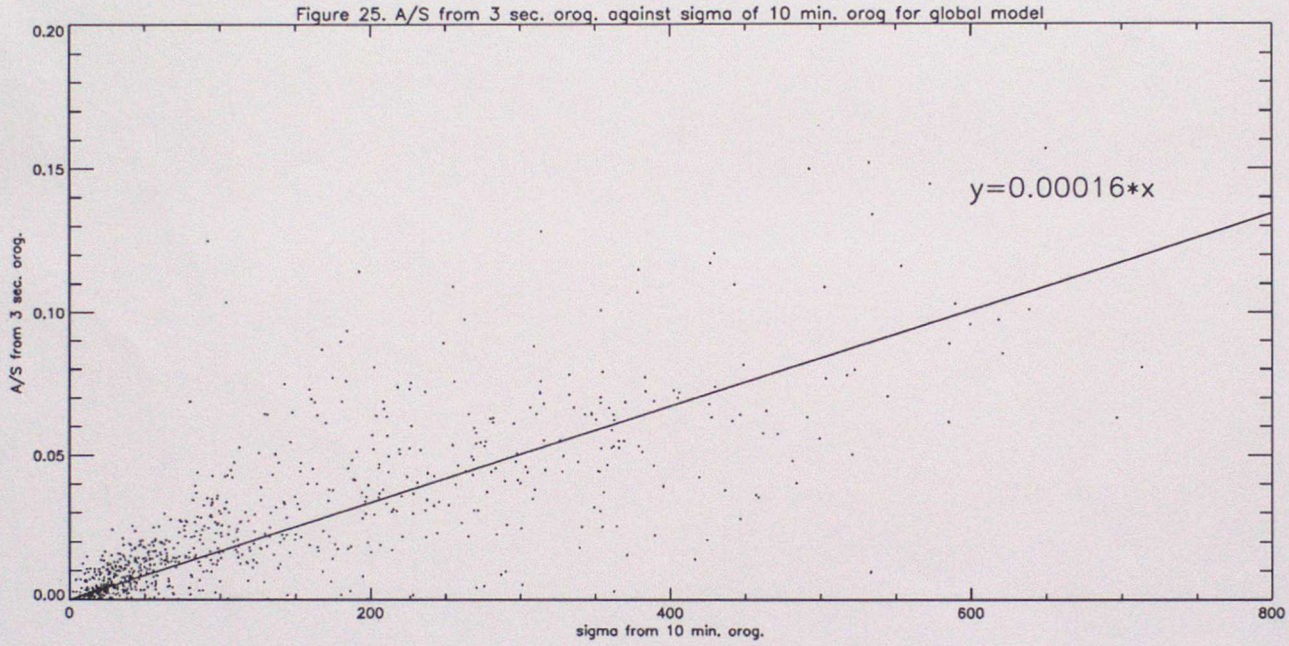


Figure 26. A/S from 3 sec. orog. against sigma of 10 min. orog for climate model

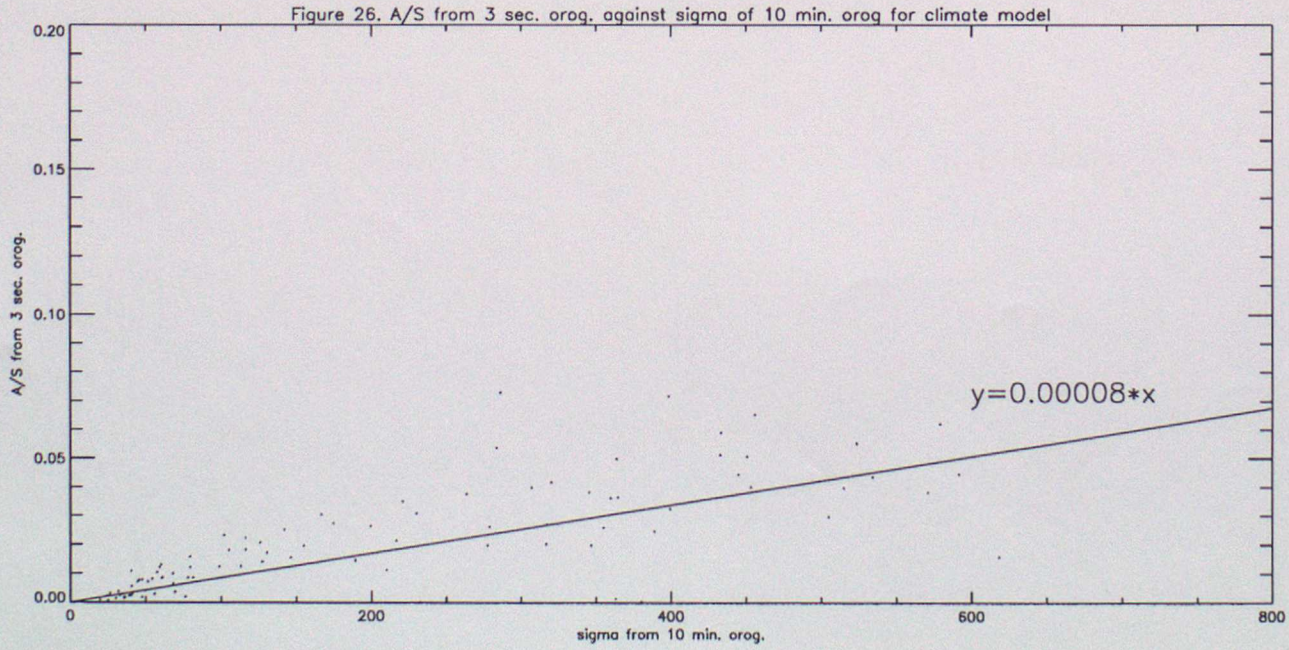


Figure 27. A/S calculated from Mason's algorithm and 3 second orography minus A/S calculated from σ of 10 minute orography for the LAM.

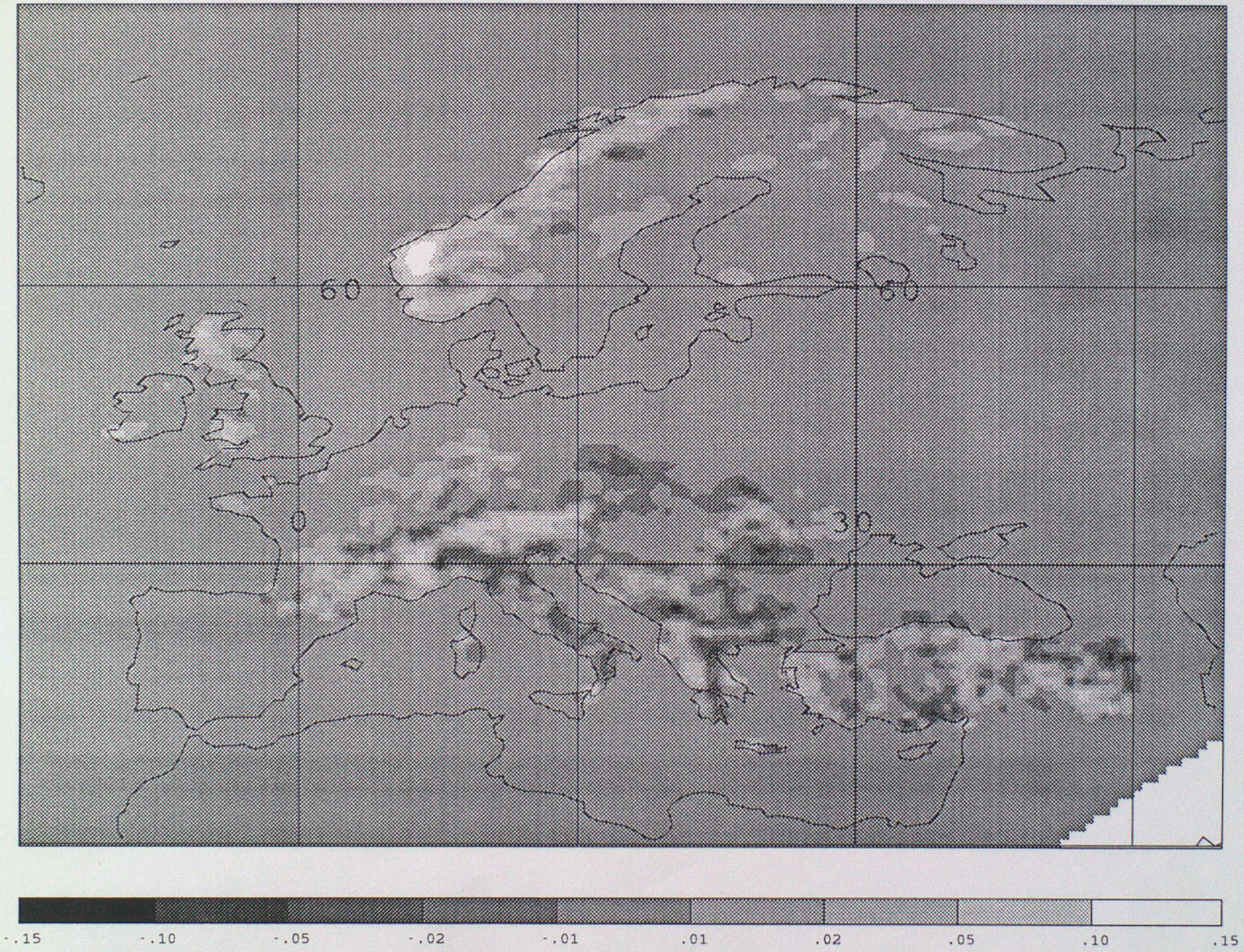


Figure 28. A/S calculated from Mason's algorithm and 3 second orography minus A/S calculated from σ of 10 minute orography for the global model.

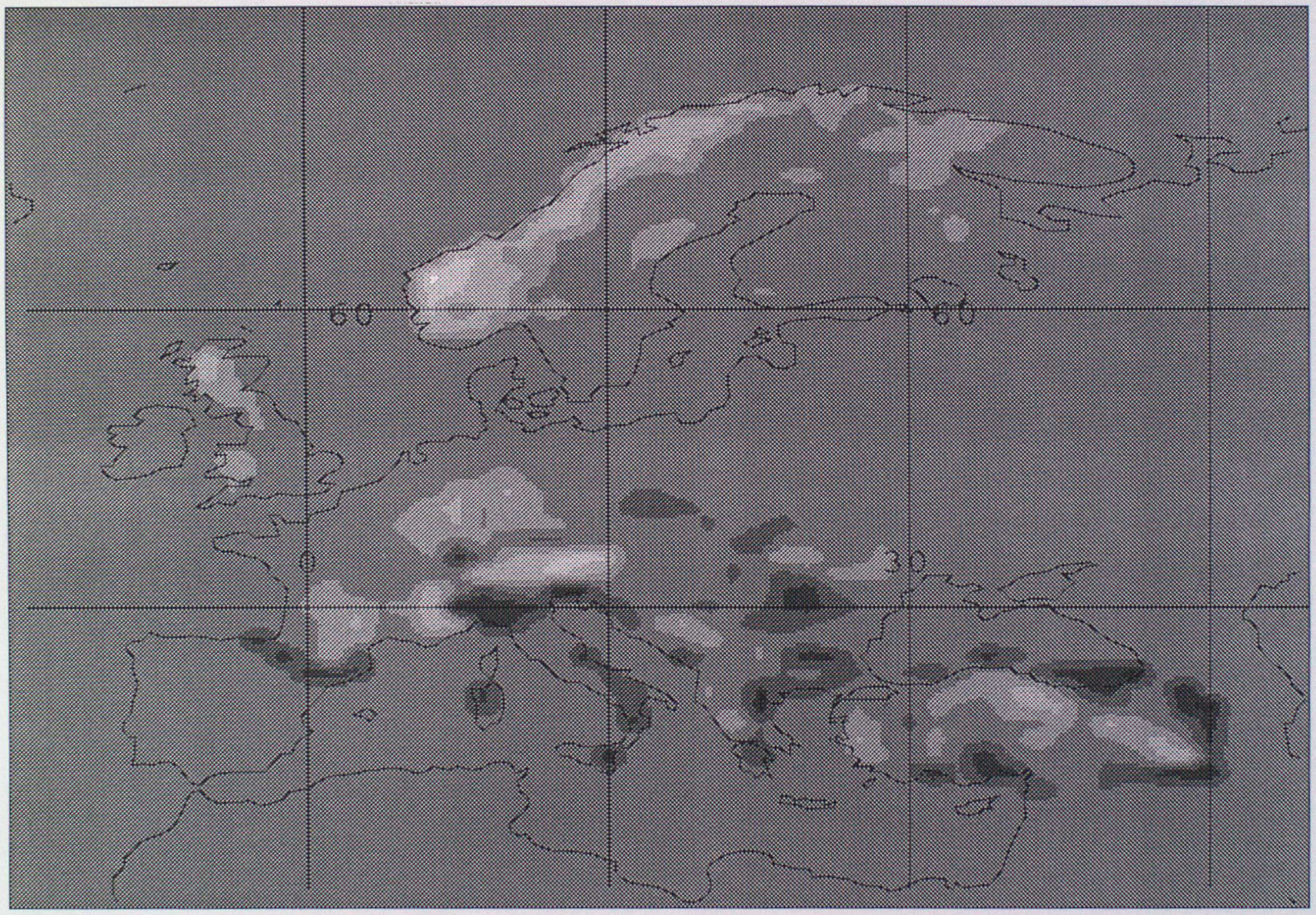
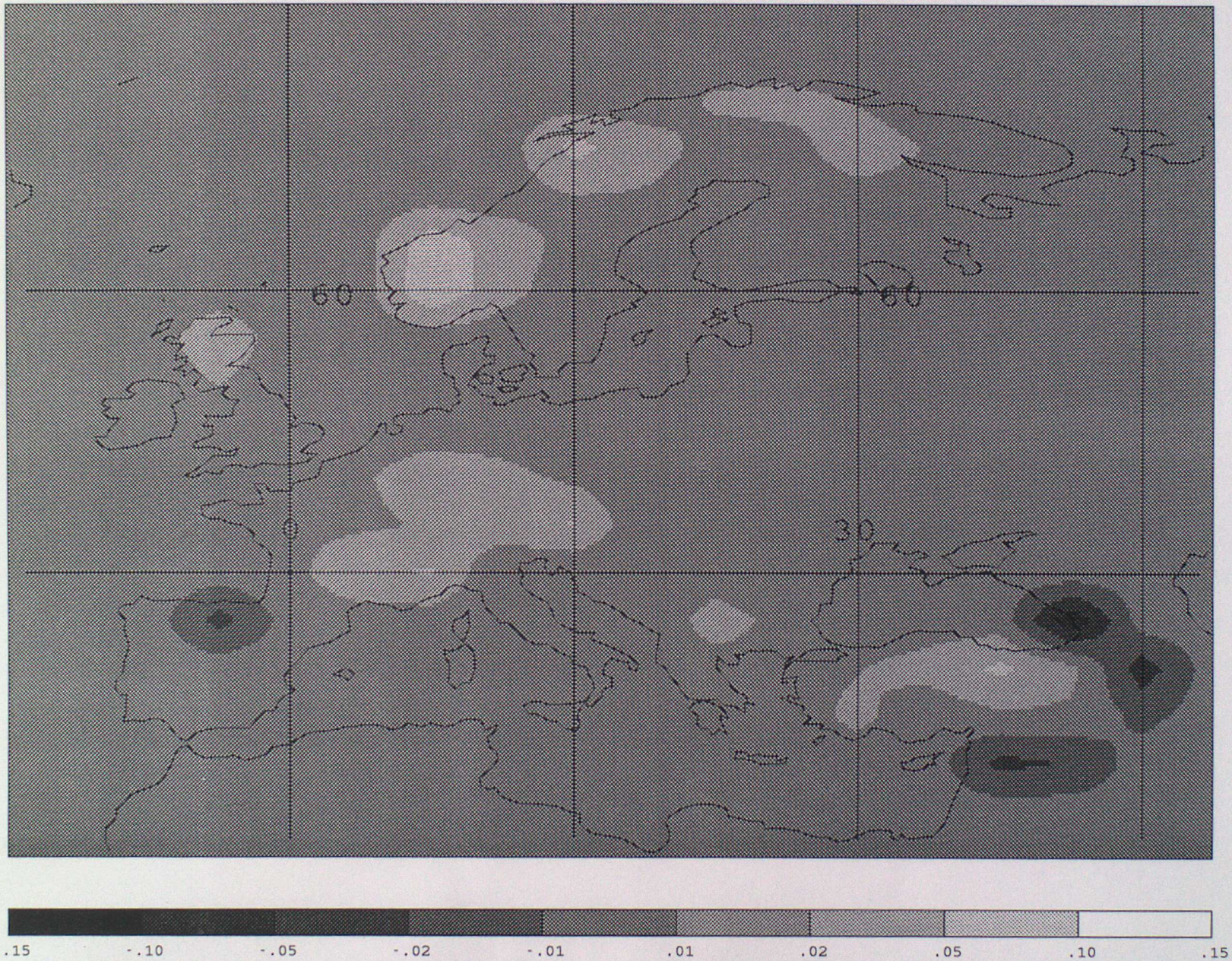



Figure 29. A/S calculated from Mason's algorithm and 3 second orography minus A/S calculated from σ of 10 minute orography for the climate model.